THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

A STUDY OF PLYBOND STRENGTH AND RELATIONSHIPS BETWEEN PLYBOND, TENSION PROPERTIES AND EDGEWISE COMPRESSION STRENGTH

Project 2906

Report Four

A Progress Report

to

FIBRE TUBE AND CORE RESEARCH GROUP

January 16, 1972

TABLE OF CONTENTS

THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

A STUDY OF PLYBOND STRENGTH AND RELATIONSHIPS BETWEEN PLYBOND, TENSION PROPERTIES AND EDGEWISE COMPRESSION STRENGTH

SUMMARY

Because members of the group expressed interest in plybond tests a limited study was carried out to compare the TAPPI plybond, ZDT and Z-direction tensile tests with regard to (1) the correlation with core performance tests such as side crush, axial crush, etc., and (2) the degree of correlation between methods. A second portion of this report is concerned with relationships between edgewise compression strength, tension properties, and plybond strength of core stock. While edgewise compression strength was found to be the property best related to core performance it is somewhat difficult to measure. Consequently, consideration of tension and plybond strengths may be an alternative to compression strength evaluation and also provide insight into ways of improving core stock performance.

The following conclusions were reached.

1. In all cases the three plybond tests gave lower correlations with the core performance tests than edgewise compression strength.

2. The Z-direction tensile test gave higher correlations with the various core performance tests than either ZDT or TAPPI plybond. In four of the five cases the ZDT gave the lowest correlation. However, except possibly in the case of side crush, the correlations with core performance were not greatly different for the three plybond tests. Such differences as exist may not be of practical significance.

3. For nominal 0.030-in. core stocks the three plybond tests were all highly intercorrelated. This would be expected because of the similar nature of

the tests. When both 0.025 and 0.030-in. core stocks were considered, TAPPI plybond was somewhat less well correlated with ZDT or Z-direction tensile. Apparently, caliper (or weight) affects TAPPI plybond somewhat differently than the other two tests and this difference in response to caliper showed up in the way the properties were related to edgewise compression strength in the second portion of the study.

4. Edgewise compression strength may be predicted with quite good accuracy from the tension and plybond properties of core stock. Best results were obtained using either tensile stiffness (ET) or tensile strength in combination with TAPPI plybond. Somewhat poorer predictions were obtained using ZDT in place of TAPPI plybond; however, it was shown that the predictions could be significantly improved by also considering board thickness. Further work is needed to clarify this point.

5. It appears that edgewise compression strength is primarily dependent on (a) the compression-buckling strength of fiber segments in the sheet and (b) the degree of fiber-to-fiber bonding. Further work to clarify this appears warranted.

INTRODUCTION

In Progress Report One relationships between various properties of the core stock and several core performance tests were studied. One of the properties was the TAPPI plybond test first described by Donahue and Verseput (1). This test utilizes the Mullen tester to apply tensile forces to the two surfaces of the sheet to cause delamination. In general, it correlated fairly well with the various core performance tests but not as well as edgewise compression strength.

There are many ways of measuring the property termed plybond strength. In this connection various members of the group indicated that the ZDT test was easier to perform and had other advantages relative to the TAPPI plybond test mentioned above. The ZDT test was developed by the American Can Co. and the tester is manufactured by Custom Scientific Instruments, Inc., Whippany, N. J. Tension forces are applied to the surface of the specimen to cause delamination; thus the test is similar in principle to the TAPPI plybond test. Another similar test is the Z-direction tensile test described by Wink and Van Eperen (2). While this is also a tensile type of plybond test it differs from the other two in that epoxy adhesive is used to adhere the specimen between two test blocks rather than two-sided pressure-sensitive tape. The apparatus was also specially designed to obtain accurate alignment of the stressing members during assembly and test.

Because of the interest expressed in plybond tests, a limited study was carried out to compare the three methods mentioned above with respect to:

(a) their correlation with core performance tests

(b) the correlation between methods

The results obtained are summarized herein.

In converting operations or end-use applications board is often subjected to stresses which cause delamination within (intraply) and/or between plies (interply). Inter- and intraply delamination may adversely affect the quality of the board and its performance in a structure such as a core. The stresses causing delamination are often classified in terms of the way in which delamination is induced. The most common type in the sense that it has been of concern longer is the case when the delaminating force is applied normal to the plane of the board. The tests mentioned above are of this type.

When board is passed through rolls, the board may delaminate due to shear forces acting parallel to the plane of the board. The resistance to this type of stress is sometimes referred to as rolling or surface shear stress. The third classification involves the case when board is bent around small radii, in which case the shear stresses induced on the interior of the board may cause delamination.

Thus, depending on the nature of the delaminating stresses, different strength properties of the board are involved and these latter need to be evaluated by different test procedures or methods. In the case of core performance tests, such as side crush or beam strength, the stresses which may cause delamination are due to shear stresses induced in the core wall by the applied load. The tensile-type plybond tests are not direct measures of shear strength. However, it appears possible that they may be correlated with shear and other board properties and this may explain, in part, their correlation with various core performance tests.

A second portion of this report discusses relationships between edgewise compression strength, the tensile properties of the board, and plybond strength. In Progress Report One it was found that edgewise compression strength was the property of the core stock which was most highly correlated with the core strength tests.

However, edgewise compression tests require considerable care in specimen preparation and tester calibration and adjustment. In view of this it was believed that it would be of interest to the group to investigate relationships between edgewise compression strength and other properties such as tensile stiffness and plybond strength which may be easier to measure. Also, information relative to such relationships may be useful in improving core stock performance and provide some insight into the mechanisms governing edgewise compression strength.

MATERIALS

The twenty-one samples of core stock obtained in connection with Phase I were utilized for this work. Seventeen of the samples had nominal calipers of 0.030 inch and four of the samples had nominal calipers of 0.025 inch.

All materials were preconditioned at 25% R.H. and 73°F. and conditioned for at least 48 hours at 50% R.H. and 73°F. prior to test.

TEST PROCEDURES

Six plybond tests were carried out on each core stock sample using each of the following test procedures:

1. TAPPI plybond: TAPPI method RC-273
2. ZDT: As per manufacturers' instructions
3. Z-direction tensile: As described in reference (2).

The TAPPI plybond results were previously reported in Report One as were the other properties of the samples referred to in this study.

DISCUSSION OF RESULTS

PLYBOND RESULTS

The results obtained using the three plybond test procedures are summarized in Table I for the twenty-one core stock samples from Phase I. The correlations between plybond strength and core strength using data taken from Report One are shown in Table II for the nominal 0.030-inch core stocks. For comparison purposes the correlations obtained with modified ring compression in Report One are also shown in the table.

It may be noted that in all cases the three plybond tests gave lower correlations with core performance than did modified ring compression strength. Of the three plybond tests the highest coefficient in each case was obtained with the Z direction tensile test. This can perhaps be attributed to the special fixtures employed in this test to maintain alignment and to uniformly stress the sample.

In four of the five cases, the ZDT test gave lower coefficients than the other two plybond tests. However, except possibly in the case of side crush the coefficients exhibited by the three plybond tests are not greatly different and the differences may not be statistically significant. From a practical standpoint, therefore, insofar as correlation with core performance is concerned it appears that the three tests are nearly equivalent. This might be expected because each is a measure of tensile strength in the thickness direction. Of the three tests the ZDT is, of course, easier to perform than either of the other two tests.

The correlations between the three tests are shown in Table III for the nominal 0.030 inch core stocks and for the composite of the 0.025 and 0.030-inch

TABLE I

PLYBOND TEST RESULTS ON CORE STOCKS

Run	Basis Weight, lb./M ft.[2]	Caliper, pt.	Density, lb./pt.	TAPPI Plybond, p.s.i.g.	ZDT Test, p.s.i.	Z-Direction Tensile, p.s.i.
1	93.8	31.1	3.0	114	61	60.0
2	111.8	32.4	3.4	167	82	107.1
3	100.7	31.4	3.2	153	76	90.7
4	80.7	27.1	3.0	127	65	68.7
5	70.1	27.0	2.6	109	61	58.4
6	82.9	25.5	3.2	137	87	112.7
7	99.7	30.4	3.3	129	67	65.8
8	102.9	31.7	3.2	177	93	119.5
9	111.0	31.5	3.5	145	74	67.6
10	98.2	30.0	3.3	144	80	83.2
11	77.6	30.8	2.5	110	49	58.4
12	109.8	34.5	3.2	132	56	56.4
13	105.9	33.1	3.2	136	62	58.8
14	106.4	31.6	3.4	173	89	96.7
15	98.5	32.0	3.1	131	62	56.2
16	104.7	33.9	3.1	139	67	64.5
17	90.5	28.0	3.2	163	83	91.6
18	105.2	32.4	3.2	141	66	65.9
19	90.7	26.2	3.5	162	81	93.0
20	93.1	31.7	3.0	121	58	54.3
21	96.9	30.0	3.2	139	66	58.7

TABLE II

CORRELATION BETWEEN CORE PERFORMANCE, PLYBOND, AND MODIFIED RING COMPRESSION TESTS FOR 0.030 IN. CORE STOCKS

(N = 17)

Core stock property	Correlation Coefficient: Side Crush	Axial Crush	Beam Strength 36 in.	Beam Strength 72 in.	Torque Strength
ZDT test	0.73	0.83	0.82	0.82	0.80
TAPPI plybond	0.80	0.86	0.83	0.81	0.84
Z-Direction tensile	0.84	0.89	0.85	0.85	0.84
Mod. ring comp., M.D.	0.87	0.90	0.90	0.92	0.87
C.D.	0.87	0.98	0.99	0.99	0.95
30°	0.89	0.93	0.91	0.94	0.88
60°	0.89	0.96	0.97	0.97	0.95

TABLE III

CORRELATION BETWEEN PLYBOND TESTS

	TAPPI Plybond	ZDT Test	Z-Direction Tensile
0.030-in. Core Stocks (N = 17)			
TAPPI plybond	1.00	0.94	0.89
ZDT test	--	1.00	0.91
0.025 and 0.030-in. Core Stocks (N = 21)			
TAPPI plybond	1.00	0.87	0.79
ZDT test	--	1.00	0.93

stocks. Graphs of the relationships between TAPPI plybond vs. ZDT test and Z-direction tensile vs. ZDT tests are shown in Fig. 1 and 2, respectively. For the 0.030-inch core stocks the three plybond tests were all highly intercorrelated as would be expected. When both 0.025 and 0.030 stocks were considered the correlations between TAPPI plybond and the other two tests declined somewhat. This occurs because the TAPPI plybond results for three of the 0.025-inch stocks were lower than would be expected on the basis of their ZDT results (see Fig. 1). On the other hand, this does not occur when Z-direction tensile is compared to the ZDT test in Fig. 2. The reasons for these differences in behavior are not clear.

It also may be of interest to note in Fig. 2 that Z-direction tensile and ZDT test results are approximately equal in magnitude at levels in the 55 to 70 p.s.i. range. If anything the ZDT results are higher than Z-direction tensile results in this range. However, at the higher test levels the Z-direction tensile results are appreciably greater in magnitude than the ZDT test results. This suggests that at the higher levels the use of adhesive to grip the specimen and the special test fixtures used in the Z-direction tensile test result in higher loads before delamination occurs than is the case in the ZDT test.

RELATIONSHIPS BETWEEN EDGEWISE COMPRESSION STRENGTH, TENSION PROPERTIES, AND PLYBOND TEST RESULTS ON CORE STOCK

As mentioned previously, the Phase I results (Report One) indicated that core strength is primarily dependent on the edgewise compression strength of the core stock. Studies in other areas have shown that edgewise compression strength is fairly well related to extensional stiffness (Et). There is however, no specific reason why a prefailure property in tension should necessarily be related to a failure property in compression except that often a strong material is also a stiff material.

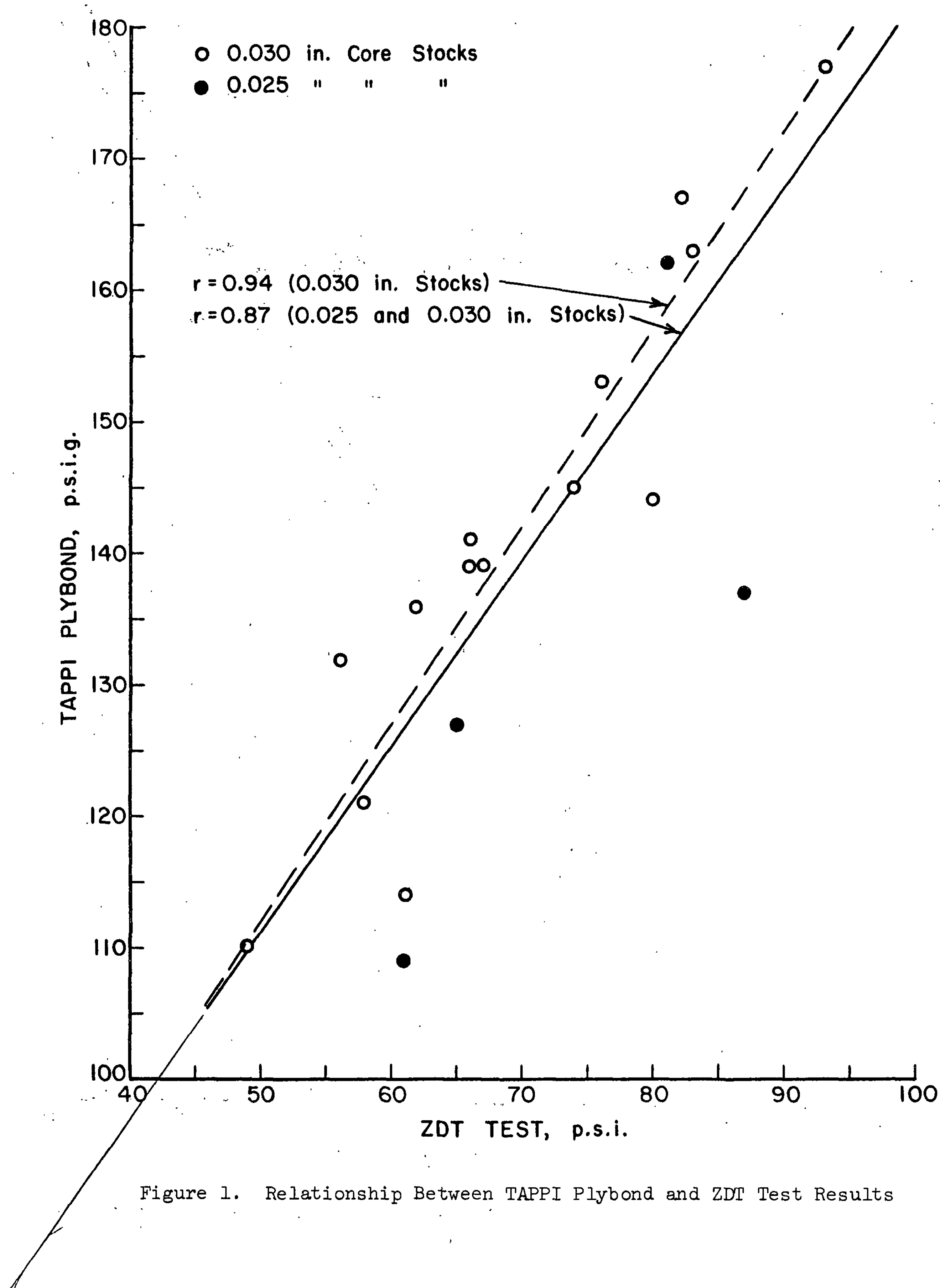

Figure 1. Relationship Between TAPPI Plybond and ZDT Test Results

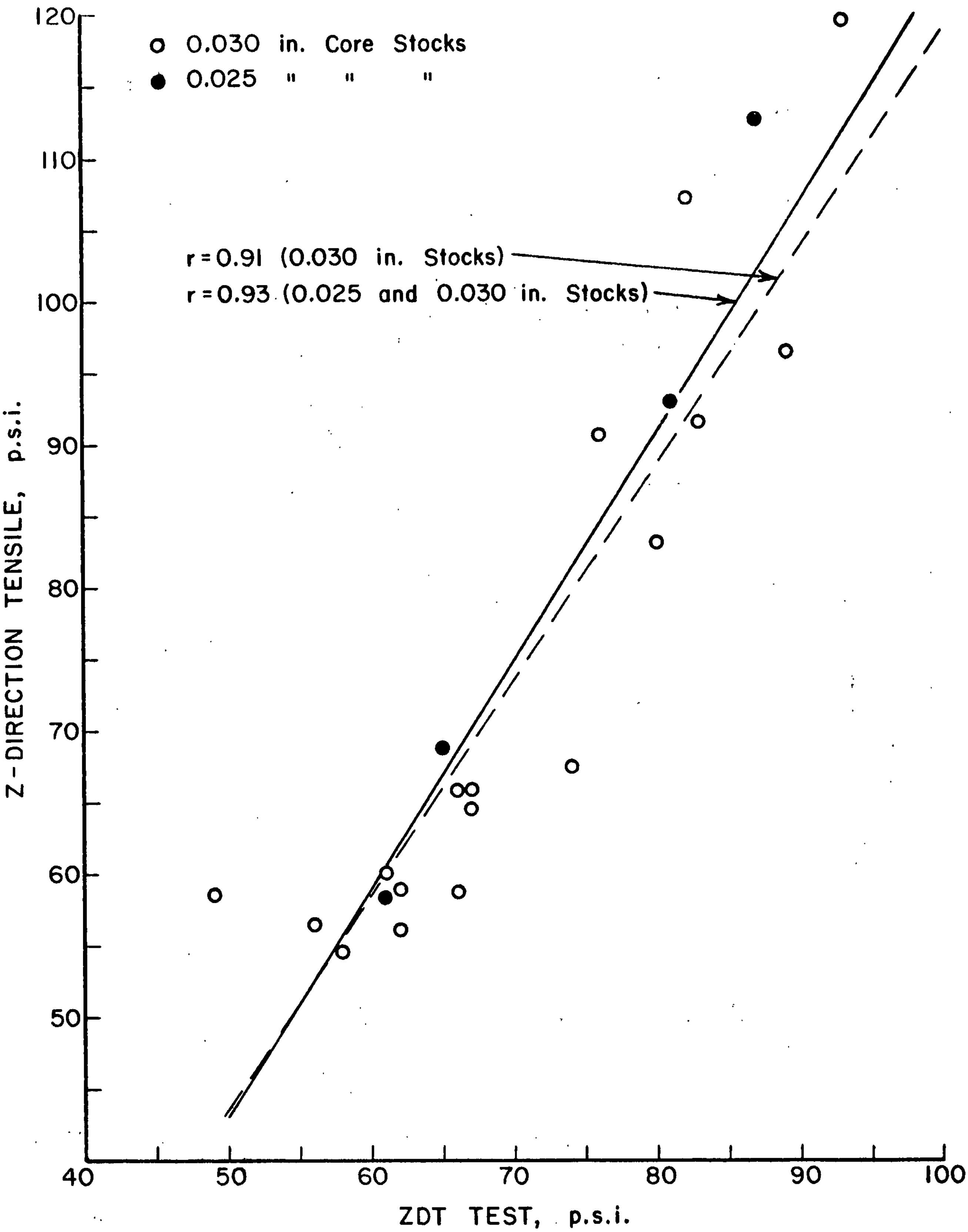

Figure 2. Relationship Between Z-Direction Tensile Strength and ZDT Test Results

Other studies relative to the effect of process variables on edgewise compression have shown that it is only weakly influenced by many variables with the exception of basis weight and possibly refining. There is also evidence which suggests that, at "low" levels of bonding, edgewise compression strength is fairly sensitive to increases in plybond which is a measure of the fiber-to-fiber bond strength in the thickness direction. However, as the plybond strength is increased, a level is reached above which only small increases in edgewise compression strength are obtained even for large increases in plybond strength.

The tensile properties of machine-made boards will normally show a much greater directional effect than edgewise compression strength. For example, cylinder-made boards often exhibit tensile strength or stiffness ratios of 4:1. Whereas their compressive strength grain ratios may be near 2:1. Setterholm and Gertjejansen (3) have presented evidence to show that compressive and tensile moduli (and stiffness) are approximately equal, and hence the compression and tensile stiffness grain ratios are about the same whereas the compressive strength grain ratio is much less. It appears that compression failure occurs as a result of a buckling of fiber segments and this is affected by fiber orientation effects somewhat differently in compression as compared to tension.

From these and other considerations it appears that edgewise compression strength is probably dependent on (a) the compression-buckling strength of fiber segments in the sheet network and (b) the degree of fiber-to-fiber bonding. Because compression measurements generally require considerable care both with respect to specimen preparation and tester adjustment it was decided to explore the tension-compression-plybond relationship for core stocks.

In Report One the results indicate that tensile strength, tensile stiffness (Et) and plybond results were all fairly well correlated with modified ring compression. Graphs of the relationship between Et and modified ring compression are shown in Fig. 3 and 4 for the MD and CD directions, respectively. It is evident there is a fairly well-defined relationship although the scatter is greater than desirable. In Fig. 4 it may be noted that the point for the fourdrinier-made stock is displaced from the points for the other stocks made on cylinder machines. This is not surprising in view of the grain ratio effects previously discussed.

Figures 5 and 6 show the relationship between modified ring compression strength and ZDT bonding for the MD and CD directions, respectively. As in the case of Et, the data point for the fourdrinier stock is displaced from the other points in Fig. 6. It also may be of interest in both figures to note that the data for the 0.025-in. stocks tends to be displaced downward from the data for the 0.030-in. stocks — i.e., for a given ZDT level a higher edgewise compression strength is obtained for the thicker stock of greater weight. This effect more or less disappears if the modified ring values are converted to stress — i.e., the load in lb./in. is divided by thickness. This indicates that core stock thickness is a factor to be taken into account when relating ZDT or Z-direction tensile tests to modified ring compression strength. Curiously, this caliper effect is not so evident when TAPPI plybond is plotted vs. modified ring compression strength as shown in Fig. 7 and 8.

With the above in mind, two-factor relationships of the following type were investigated using data for the 20 cylinder-made core stocks from Phase I.

(a) Modified ring compression vs. Et and either TAPPI plybond or ZDT test results

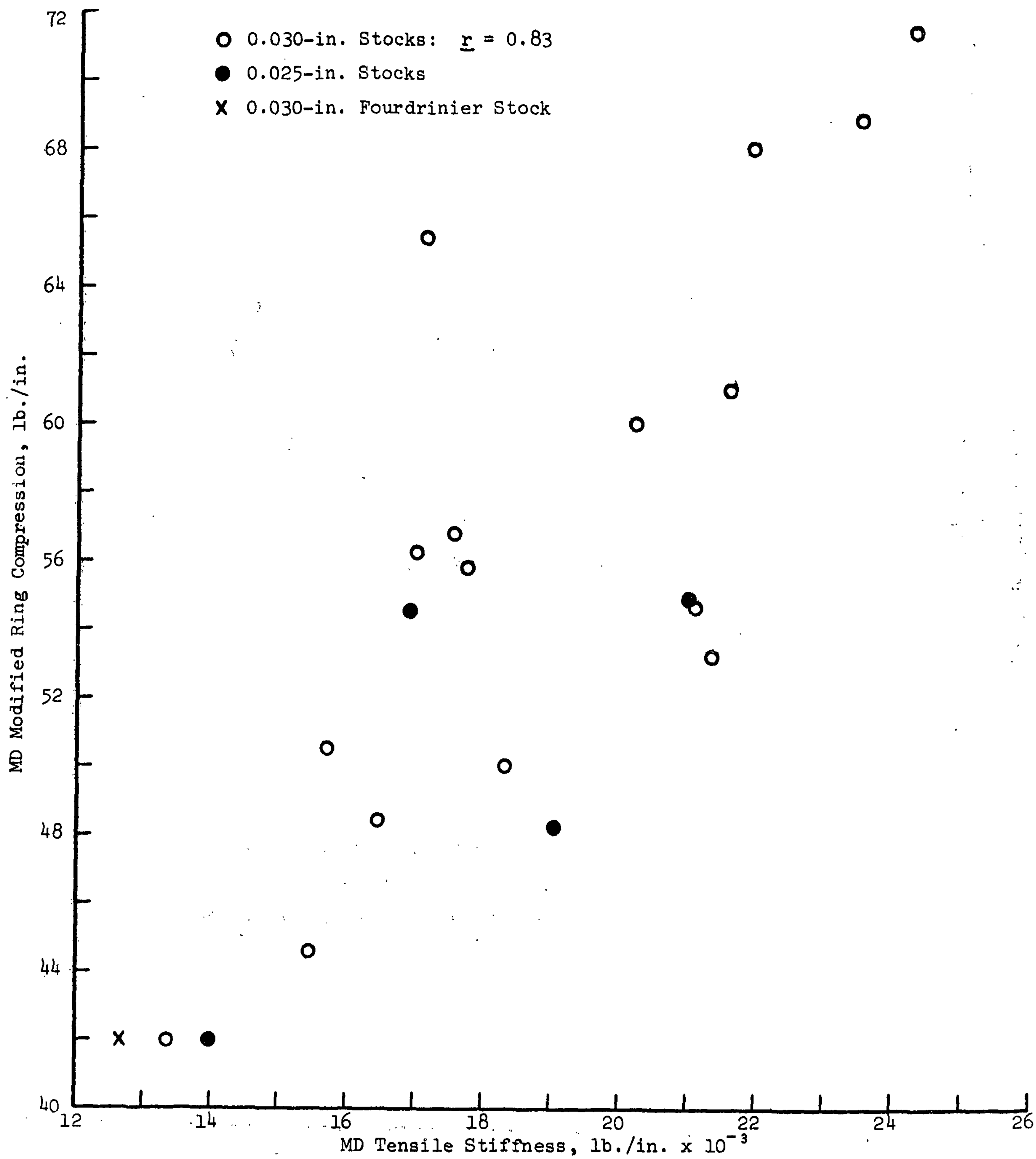

Figure 3. Relationship Between MD Tensile Stiffness (Et) and Modified Ring Compression Strength

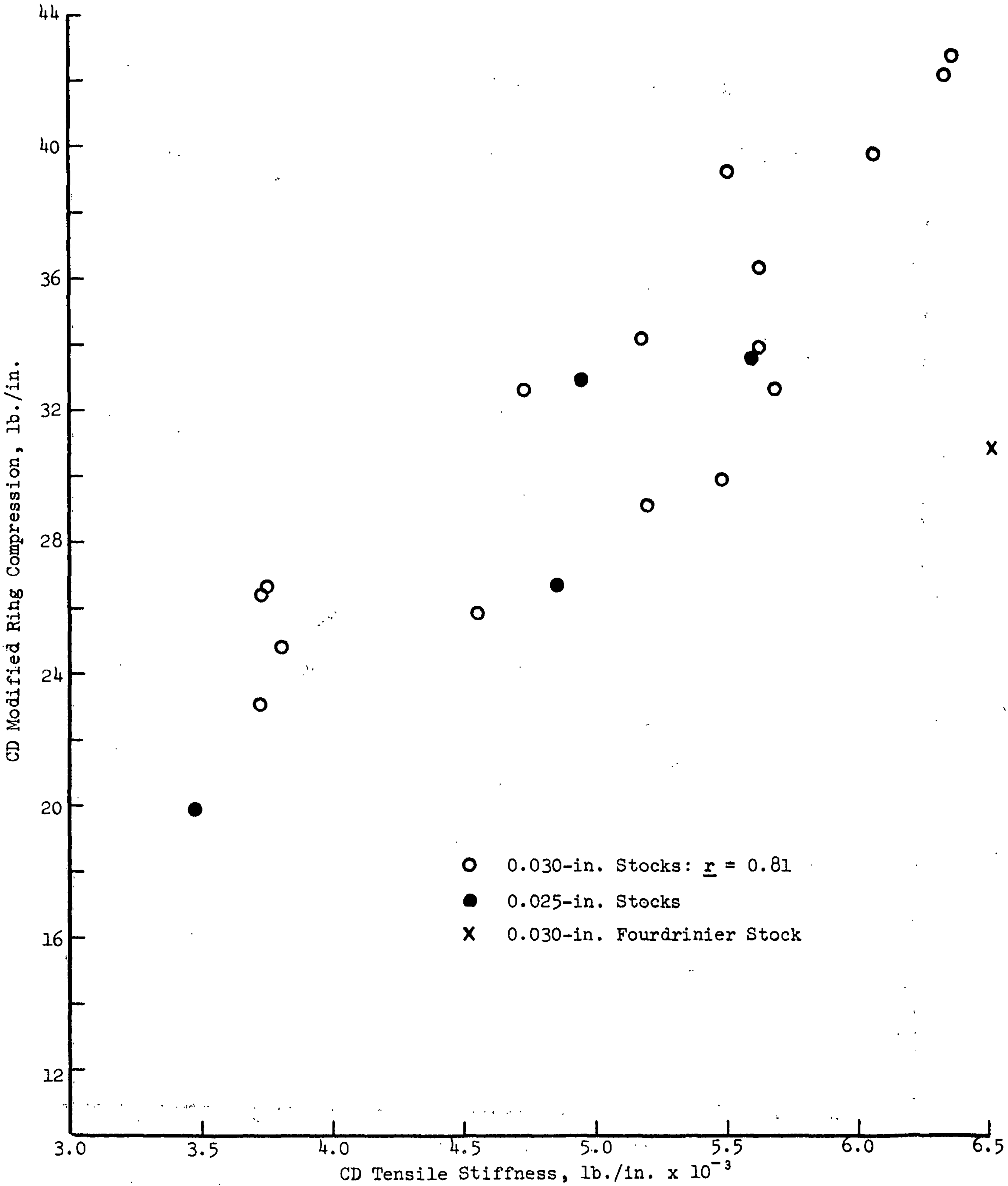

Figure 4. Relationship Between CD Tensile Stiffness (Et) and Modified Ring Compression

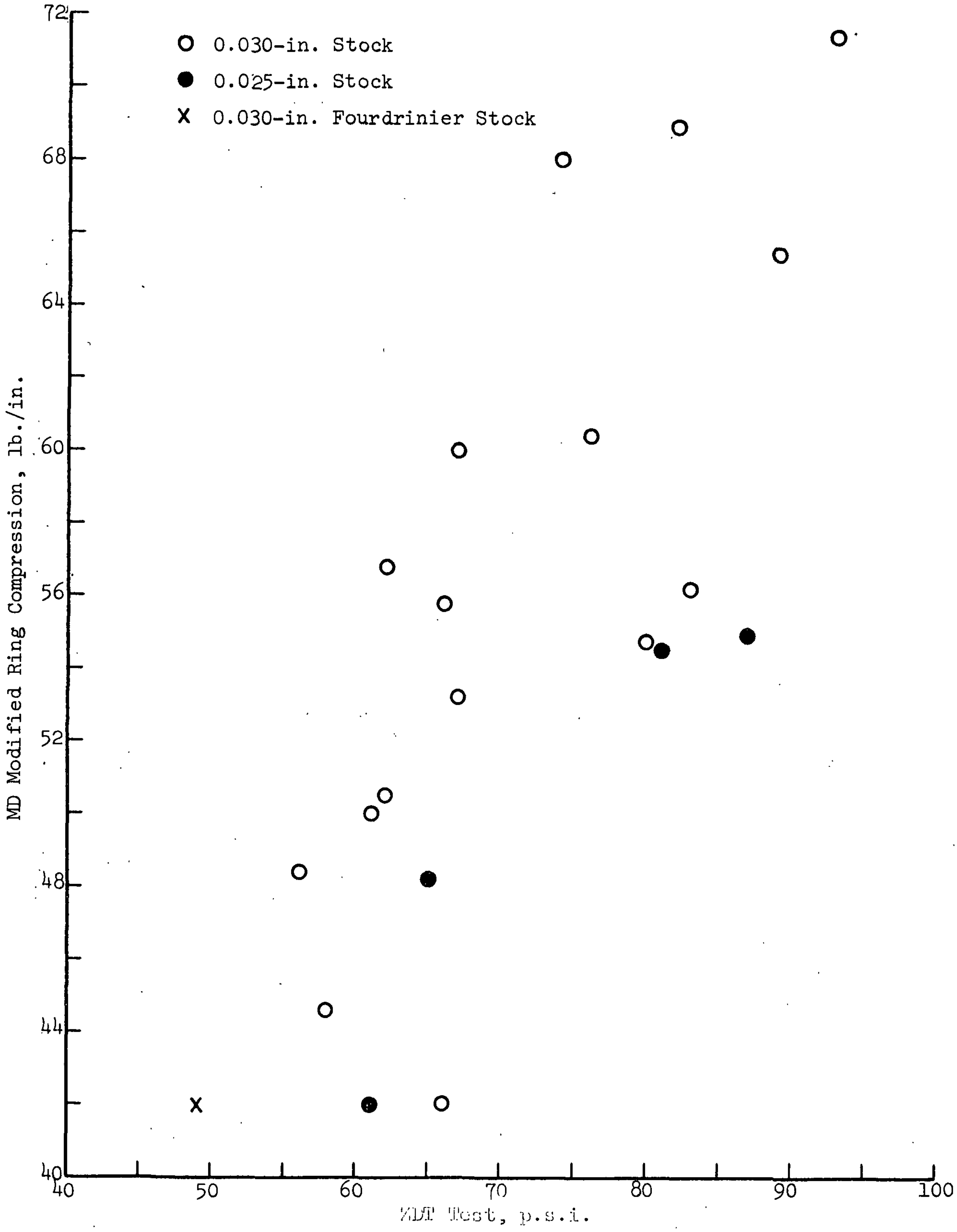

Figure 5. Relationship Between MD Modified Ring Compression Strength and ZDT Strength

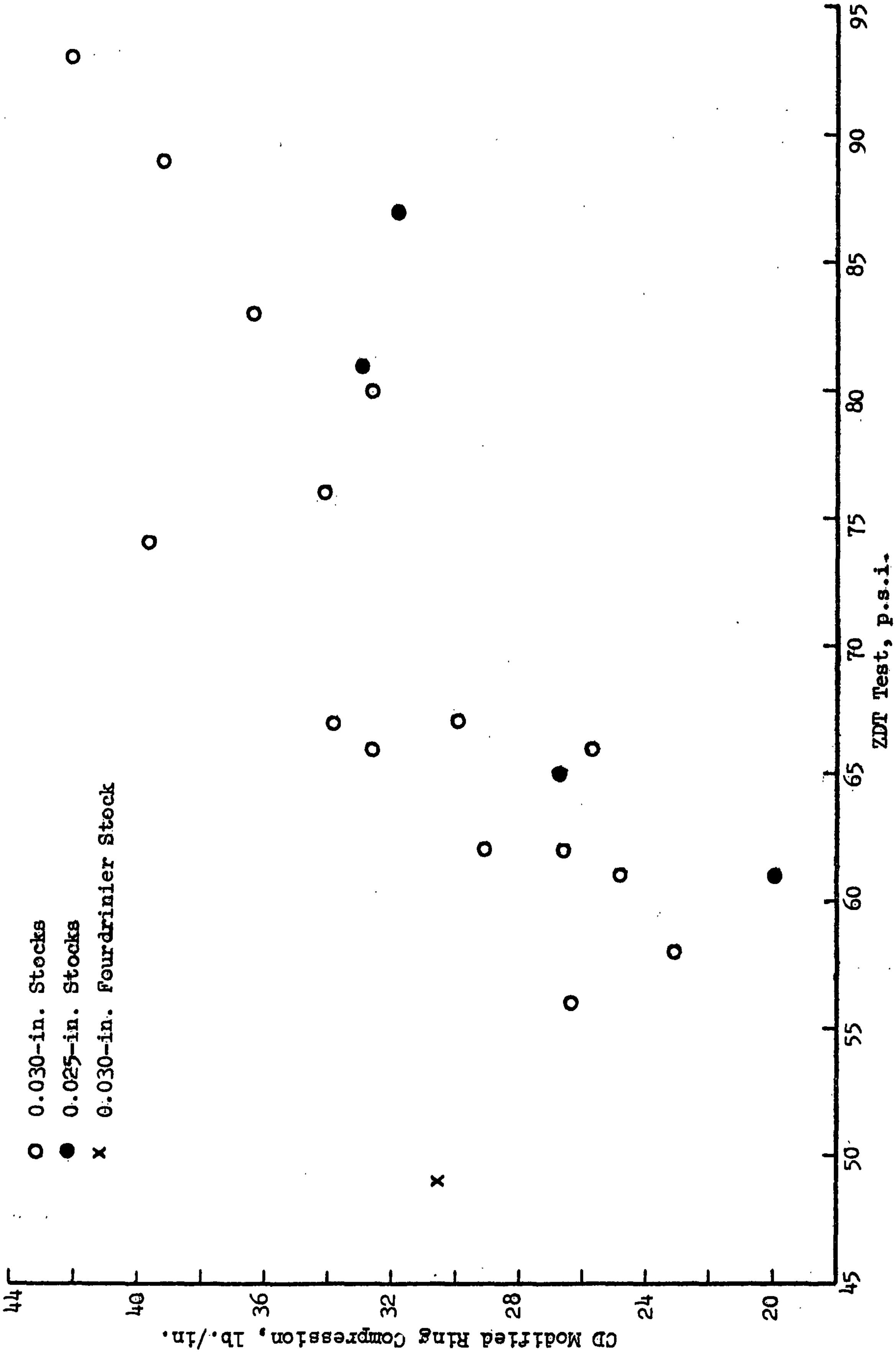

Figure 6. Relationship Between CD Modified Ring Compression and ZDT Strength

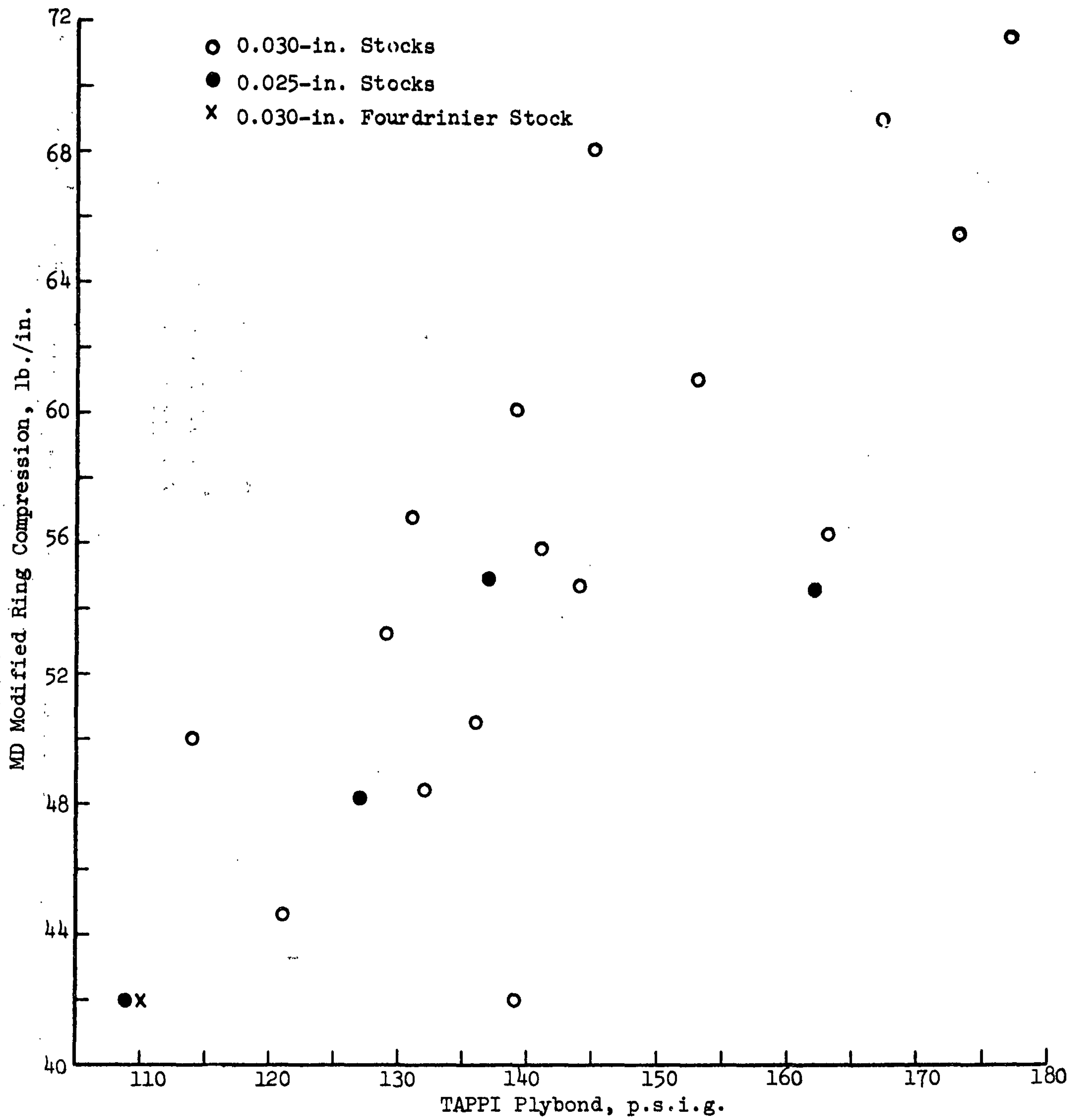

Figure 7. Relationship Between MD Modified Ring Compression Strength and TAPPI Plybond

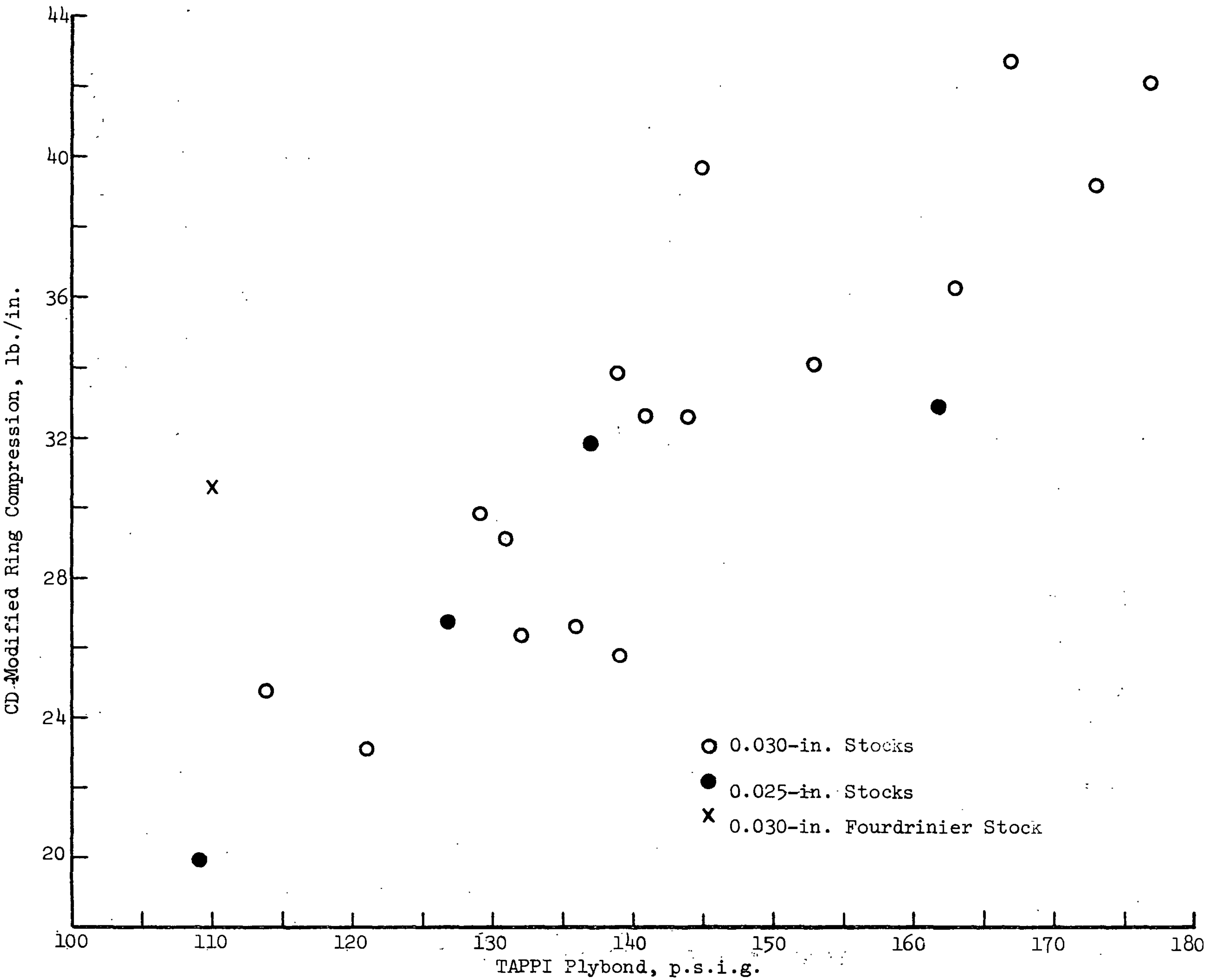

Figure 8. Relationship Between CD Modified Ring Compression Strength and TAPPI Plybond

(b) Modified ring compression vs. tensile strength and either TAPPI plybond or ZDT test results.

The results obtained are summarized in Table IV. Significant two-factor relationships were obtained for all four ring compression orientations using either Et or tensile strength in combination with TAPPI plybond. The average prediction errors ranged from about 4.5 to 5.3% depending on orientation for Et and TAPPI plybond. For tensile and TAPPI plybond the average prediction errors ranged from about 3.9 to 4.9%. The above results indicate that modified ring compression strength is well related to the tension properties of the board in combination with TAPPI plybond strength.

When ZDT test results were used in combination with either tensile strength or Et the prediction errors were slightly higher than obtained with TAPPI plybond and the significance levels for ZDT strength were in a number of cases at the 0.10 level or more — i.e., not significant at even the 0.10 level. The higher prediction errors may be traceable to the different effects of caliper on the ZDT and plybond tests and additional work in this area is warranted.

In general, the regression coefficients for either tensile or Et increase in a regular manner as the orientation varies from the MD to CD. This would be expected because of the grain ratio differences between tension properties and edgewise compression strength. On the other hand, the regression coefficients for either TAPPI plybond or ZDT strength are highest for equations predicting MD strength, pass through a minimum at the 60° orientation and increase again for the CD orientation. Taken at face value this suggests that plybond strength is less important for tests at intermediate orientations than in MD or CD tests. There appears to be no clear reason for this result.

TABLE IV

TWO-FACTOR REGRESSION EQUATIONS FOR PREDICTING
MODIFIED RING COMPRESSION (MR) STRENGTH

No.	Orientation	Var 1[a] (X_1)	Var 2[a] (X_2)	Regression Coefficient: Constant	Regression Coefficient: Var 1	Regression Coefficient: Var 2	Sign. Level: Var 1	Sign. Level: Var 2	Mult. Corr. Coeff.	Av. Pred. Error, %
1	0 (M.D.)	Et	PB	-7.04	0.001524	0.2387	0.01	0.01	0.916	5.09
2	30	Et	PB	-7.44	0.001948	0.2050	0.01	0.01	0.931	5.34
3	60	Et	PB	-6.03	0.003048	0.1573	0.01	0.01	0.939	5.28
4	90 (C.D.)	Et	PB	-11.15	0.003701	0.1699	0.01	0.01	0.961	4.51
5	0 (M.D.)	T	PB	4.14	0.1320	0.2079	0.01	0.01	0.899	4.92
6	30	T	PB	-4.52	0.3270	0.1323	0.01	0.05	0.938	4.52
7	60	T	PB	-4.05	0.4540	0.1162	0.01	0.01	0.957	3.91
8	90 (C.D.)	T	PB	-9.80	0.5001	0.1429	0.01	0.01	0.961	4.70
9	0 (M.D.)	Et	ZDT	4.70	0.001564	0.2981	0.01	0.05	0.849	6.54
10	30	Et	ZDT	4.01	0.002232	0.1992	0.01	0.10	0.866	7.05
11	60	Et	ZDT	2.11	0.004240	0.0884	0.01	NS	0.891	7.07
12	90 (C.D.)	Et	ZDT	-3.55	0.004682	0.1618	0.01	0.10	0.912	7.09
13	0 (M.D.)	T	ZDT	11.66	0.1443	0.2782	0.01	0.05	0.869	5.30
14	30	T	ZDT	0.67	0.3736	0.1288	0.01	NS	0.922	5.63
15	60	T	ZDT	-0.34	0.5406	0.1149	0.01	0.10	0.945	5.01
16	90 (C.D.)	T	ZDT	-7.21	0.5842	0.1974	0.01	0.01	0.959	4.28

[a]Equation $\underline{MR} = \underline{a} + \underline{b}\,\underline{X}_1 + \underline{c}\,\underline{X}_2$.

Note: Symbols are as follows:

Et = tensile stiffness in indicated orientation.
T = tensile strength in indicated orientation.
PB = TAPPI plybond.
ZDT = ZDT test.
MR = modified ring compression in indicated orientation.

As an illustration that thickness (or weight) may also be a factor to be considered, regression equations were obtained using the following factors:

1. Tensile stiffness, ZDT or TAPPI plybond, and caliper $\underline{t}$
2. Tensile stiffness, and the product of caliper times ZDT or TAPPI plybond.

The results obtained are summarized in Table V. It may be noted that caliper was a very significant factor in the regression equations involving ZDT strength and materially improved the accuracy of the predictions (compare Tables IV and V). The inclusion of caliper in the equations involving plybond also produced some improvement in prediction error but the caliper effect was less than in the case of the equations involving ZDT.

In brief summary the results indicate that modified ring compression strength is quite well related to tension properties and plybond strength. These relationships may prove to be useful in controlling and improving edgewise compression strength.

TABLE V

REGRESSION EQUATIONS INCORPORATING TENSILE STIFFNESS, PLYBOND AND THICKNESS

No.	Regression Equation	Significance Level Var. 1	Var. 2	Var. 3	$\underline{R}$	Av. Pred. Error, %
1	$P_{mx} = 0.00105(Et)_x + 0.478\ ZDT + 1449\ t - 43.0$	0.01	0.01	0.01	0.932	4.42
2	$P_{mx} = 0.00101(Et)_x + 16.36\ t\ ZDT + 0.6$	0.01	0.01	--	0.930	4.02
3	$P_{my} = 0.00338(Et)_y + 0.305\ ZDT + 870\ t - 33.9$	0.01	0.01	0.01	0.964	4.08
4	$P_{my} = 0.00312(Et)_y + 10.65\ t\ ZDT - 7.4$	0.01	0.01	--	0.962	4.38
5	$P_{mx} = 0.00147(Et)_x + 0.237\ PB + 622\ t - 24.7$	0.01	0.01	0.10	0.934	4.35
6	$P_{mx} = 0.00150(Et)_x + 6.81\ t\ PB - 2.3$	0.01	0.01	--	0.929	4.80
7	$P_{my} = 0.00389(Et)_y + 0.160\ PB + 381\ t - 22.3$	0.01	0.01	0.05	0.973	3.53
8	$P_{my} = 0.00439(Et)_y + 4.15\ t\ PB - 8.5$	0.01	0.01	--	0.968	4.28

Note: Symbols as follows:

P_{mx}, P_{my} = modified ring strength in MD and CD direction, respectively, lb./in.

$(Et)_x$, $(Et)_y$ = tensile stiffness in MD and CD directions, respectively, lb./in.

ZDT = Z-direction tensile, p.s.i.

TP = TAPPI plybond, p.s.i.g.

$\underline{t}$ = thickness, inch.

$\underline{t}$ ZDT, $\underline{t}$ TP = product of thickness times ZDT and TAPPI plybond, respectively.

LITERATURE CITED

1. Donahue, J. F., and Verseput, H. W., Tappi 40, no. 5:311-13(May, 1957).

2. Wink, W. A., and Van Eperen, R. H., Tappi 50, no. 8:393-400(Aug., 1957).

3. Setterholm, V. C., and Gertjejansen, R. D., Tappi 48, no. 5:308-13(May, 1965).

THE INSTITUTE OF PAPER CHEMISTRY

W. J. Whitsitt

William J. Whitsitt
Research Associate

R. C. McKee

Robert C. McKee
Chairman
Container Section